LCA Methodology

The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection

Part 1: A Means to Systematically and Quantitatively Select LCA Boundaries

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Abstract. Life-cycle assessment (LCA) is being used more and more as a decision making tool to compare alternative systems of providing a given product or service. Each system is theoretically made up of a near infinite number of elements or unit processes to produce the product or service. In practice, time and resources to complete an LCA are limited, hence the need to draw practical boundaries on the systems being analyzed. However, how does the LCA practitioner draw fair boundaries on two or more different systems being compared? In other words, how does one decide which unit processes to include in each system? A consistent quantitative method of selecting boundaries is essential for comparative LCA studies.
This paper first outlines the requirements for a system boundary selection methodology and then demonstrates the shortfalls of existing methods. The primary objective is to present the Relative Mass-Energy-Economic (RMEE) method for system boundary selection. This concise, repeatable and quantitative method for selecting system boundaries for LCA is demonstrated on a life-cycle system for ethanol fuel. Unlike many other methods of selecting system boundaries, the RMEE method is practical to use and quantitatively ensures different systems have similar system boundaries to ensure a fair comparison between options. The RMEE method has been designed specifically for LCA studies of energy systems.

Keywords: Comparative assertions; LCA; Life Cycle Assessment (LCA); relative mass-energy-economic (RMEE); RMEE; system boundary selection

1 Introduction

As life-cycle assessment (LCA) becomes a common tool to aid in making business and policy decisions, it is crucial that the methodology become more rigorous and transparent [Total Life-cycle Conference 1997, 1998] [1,2]. Since decision making and design improvement involves making choices, it is inevitable that LCA will be used to compare alternative systems providing a similar product or service. Good selection/rejection decisions between system options requires that systems be comparable not only in the products or services they provide, and in data quality, but also in the depth of detail included/excluded in each system's analysis. In other words, it is es-sential to have a rigorous method of deciding which elements, or unit processes, of a system are to be included in an LCA analysis such that a "fair" comparison between systems results. The LCA standards of ISO 14000 recognize this by stating,

"In comparative studies, the equivalence of the systems being compared shall be evaluated before interpreting the results. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, **system boundaries**, data quality, allocation procedures, decision rules on evaluating inputs and outputs and impact assessment." [3].

Because of the importance of system boundary selection (SBS), the ISO standard requires disclosure of the system boundary selection (SBS) method used "The criteria used in establishing the system boundaries **shall** be identified and justified in the scope of the study." [3].

There are several aspects or "dimensions" involved in selecting system boundaries. System boundary dimensions identified by Tillman et al. [18] are as follows:

I. boundaries between the technological system and nature,
II. geographical area,
III. time horizon,
IV. production of capital goods,
V. boundaries between the life-cycle system of the studied product (or service) and the connected life-cycle systems of other products.

This work focuses on developing a method to select boundaries of dimension V, between the life-cycle system of the studied product or service and the connected life-cycle systems of inputs to the primary life-cycle system. Because the production of capital goods can be considered a connected life-cycle system, the methodology developed in this paper is also applicable to dimension IV of system boundary selection. An-

other element of dimension V is the analysis of outputs and how they are included or excluded in the system. Waste outputs often require further, sometimes intensive, downstream processing (e.g. hazardous waste treatment, waste collection/ sorting/ disposal/ monitoring). The question is whether or not these processes or services are systematically included or excluded in the boundary of the life-cycle system. Because these services have a cost associated with them, the method proposed here is equally applicable to answer this question. A second category of outputs requiring system boundary consideration is co-products and by-products. These are products and non-waste outputs, respectively, which do not contribute to the functional unit of concern [4]. Nonetheless, co-products and by-products share processes in the life-cycle stages of the primary product system, and their contribution (or share of responsibility) needs to be determined and properly allocated. Evaluation of allocation methods is not completed here.

Material and energy inputs within the system boundary of an LCA typically encompass various life-cycle stages including raw materials acquisition, manufacturing, transportation, use/reuse/maintenance, and recycle/waste management [5]. The classical figure, presented by FAVA et al, illustrating these boundaries is shown in Fig. 1 [5]. The general practice and objective of system boundary selection is summarized by BOGUSKI et al. [6]:

"After all the steps that fall within the system boundaries are identified, the practitioner may choose to simplify the LCI or LCA by excluding some steps from the study. This must be done with extreme caution and only after the entire system has been examined. The general rule for excluding steps from the study is that a step may be excluded only if doing so does not change the conclusions of the study."

The major difficulty of this general rule is how does one prove a step will not change the conclusions without first completing the LCA? If one must collect data to prove this, then why exclude the step if the data exists and has been included in the LCA? Furthermore, to test if a particular "step" in the life-cycle affects the conclusions one must have assumed a system boundary to begin with. In short, this rule is not practical for LCA practitioners who must make rigorous comparative decisions with limited time and resources. The Relative Mass-Energy-Economic method for system boundary selection allows the LCA practitioner to select system boundaries and exclude unit processes or "steps" from the study before examining the entire system and to do this in a practical, repeatable and quantitative means.

The three objectives of this paper are:

1. to thoroughly review the current practice of system boundary selection in the field of LCA,
2. to demonstrate the need for a rigorous method for selecting LCA system boundaries, and
3. to present the development of a new system boundary selection (SBS) method called the Relative Mass-Energy-Economic (RMEE) method for system boundary selection.

RMEE is revealed to be practical, repeatable, and quantitative – qualities missing to varying degrees from existing LCA system boundary selection methodologies.

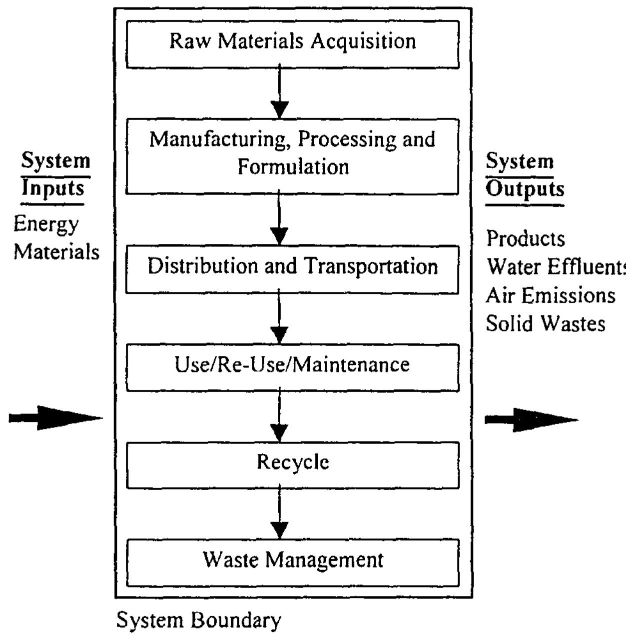

Fig. 1: General LCA system boundaries

2 Characteristics of Good System Boundary Selection Methodology

In theory, the system describing the entire "cradle-to-grave" life-cycle of a product or process is nearly infinite. One could take a given product system to such detail as to include the entire manufacturing and material extraction for a wheel bolt of a truck transporting office paper to a refinery to produce gasoline, and beyond. Indirectly every product or process is connected within the global economic web. This is not practical for the LCA practitioner (although there is an interesting body of research developing at Carnagie-Mellon University using macro-economic input-output analysis to model the interconnected economy and potential environmental loading) [7].

The ultimate objective of a LCA is to identify and quantify all significant environmental outputs associated with the product or service system. As ISO 14041 states: "Resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study." [3]. In practice, the LCA practitioner does not have the resources available to quantify all the environmental outputs of all the unit processes in a system and then identify which unit processes significantly contribute to the overall life-cycle environmental outputs of the desired product. Due to limited time and resources for completing LCA decisions, the practitioner must be able to draw system boundaries without having to first quantify the environmental outputs of any unit process.

LCA can often be very subjective, potentially resulting in questionable and highly debatable results. As a result, external verification is essential to current LCA practices. One area of debate is often whether or not a comparative LCA is actually making a comparison between life-cycle systems with equivalent resolution of system inputs and outputs [1].

That is, how does one know two competing systems are be compared with equivalent system boundaries? System boundary selection based on qualitative parameters does not allow for repeatability, resulting in questionable results. As a result, the SBS method must be quantitative and repeatable.

As anyone who has completed an LCA knows, it requires significant time and resources to complete a study. Furthermore, the general trend is to streamline LCA methods to allow faster decision making without the need of excessive resources and time. As a result, a good SBS method must also be simple enough to apply and aid in the efforts of streamlining LCA.

Since the objective of an LCA is to calculate the potential environmental impact of a system, the SBS method cannot be based only on the inputs and outputs of a unit process without considering the significance of the role of the unit process in the life-cycle system. The reason for this is a particular input or output to a unit process may be significant to the unit process, but the unit process itself may not be significant to the environmental performance of the whole life-cycle system. If the SBS method decides which inputs should be included in a system based on the unit process alone, then significant time will be spent collecting and analyzing data which, in the end, could be insignificant to the decision being made about the life-cycle systems. For example, consider a transportation unit process utilizing diesel fuel. The diesel fuel is a significant input to this unit process but it may be insignificant relative to the life-cycle system as a whole.

Ultimately, the selection of the system boundary affects the completeness or scope of the life-cycle system. The system boundary discriminates between what is within the LCA analysis and what is left outside of the LCA. To allow for a fair comparison between systems the goal is to have systems of similar completeness. Furthermore, in general, the more complete a system is, the greater the time and resources required to obtain and analyze data. It is also true that 100% system completeness is not only impossible to achieve but is also not required to make an educated decision between products or services. As a result, a good SBS method should be able to define different levels or measures of completeness to allow for fair comparisons, and the flexibility to complete streamlined or more detailed LCAs. The method developed within this paper aims to provide this.

In summary, to be efficient and provide a repeatable and rigorous comparison between systems, the SBS method must

1. be quantitative (i.e. qualitative judgement rules are not adequate),
2. not require the quantification of environmental outputs from every unit process in the life-cycle system before system boundary selection,
3. be simple and allow for streamlining (i.e. the SBS method must allow for different degrees of rigor due to varying availability of time and resources to make decisions),
4. consider the significance of inputs and outputs relative to the system as a whole, not only to an individual unit process,
5. provide the ability to define measurable levels of system completeness.

3 Current System Boundary Selection Procedures

The ISO 14040 document [8] recognizes different methods of SBS exist, and also the potential shortfall of the mass percentage method –

"There are several criteria that are used in LCA practice to decide which inputs will be studied, including 1) mass, 2) energy, and 3) environmental relevance. Making the initial identification of inputs based on mass contribution alone may result in important inputs being omitted from the study. [8]".

The following discussion reviews the various existing methods of SBS currently being practiced.

Many LCA studies arbitrarily and qualitatively select system boundaries by considering only the "main" life-cycle stream [9,10]. These qualitative methods do not allow for repeatable boundaries to be selected, nor do they ensure similar boundaries are selected for different systems.

Other LCAs have used the percentage of the mass of unit process mass inputs to cut system boundaries which is a first step to a quantitative method of SBS [11]. However, this method considers only the inputs to a given unit process with respect to its self by calculating the percent each input contributes by mass to the total unit process inputs. A cut-off ratio is then chosen. The cut-off ratio is often 0.05 or 0.10 meaning any input contributing less than this ratio is considered insignificant to the unit process and is then not studied further upstream. The major disadvantage of this method is it considers only the relationship of each input to a unit process and not its significance to the entire life-cycle system.

Fig. 2 (*p. 40*) illustrates the system boundary selection method by mass percentage of unit process inputs where a cut-off criteria of 0.05 or 0.10 by mass would consider Input C to be insignificant but require upstream analysis of both Input A and Input B. Although Input A and Input B may be significant inputs to Unit Process 101, relative to the system as a whole they may be completely insignificant. As a result, the LCA practitioner may waste substantial time and resources searching for and analyzing data upstream of Inputs A and B which in the end will have no impact or relevance to the end result of the complete system analysis. On the other hand, if Unit Process 101 is near the downstream end-point (i.e. closely linked to the functional unit), Input C could be a significant input to the functional unit. Yet, by considering only the ratio of unit process inputs it would be eliminated from the system with a 0.05 rule.

Obtaining data for a life-cycle assessment is often the most costly step. As a result, many LCA studies choose system boundaries based on what data can be most readily obtained [12]. If data for a particular unit process are considered difficult and costly to obtain, the practitioner might be more easily persuaded to exclude it from the system boundary. The reverse is also true, where simply because the data is available the unit process will be included in the system boundaries. One might claim, by including these unit processes the study is that much more complete and "detailed". Two problems arise from including unit processes only because the data is available:

1. A false sense of completeness or detail can be interpreted when unit processes known to be relatively insignificant are included. The audience of the LCA study might interpret this as the entire LCA having been investigated to a similar level of detail.
2. When comparing life-cycle systems for decision making it is necessary that all systems be similarly complete [3]. The addition of unit processes with data to one system may make that particular system more complete, but if similar detail is not added to the other systems the comparison becomes biased.

In short, defining system boundaries based on data availability is an unacceptable method because it is not repeatable, has no scientific justification, and is not rigorous.

The ISO criteria of "environmental relevance" is not practical because it requires one to evaluate the environmental outputs for every unit process in a system before system boundaries can be drawn. In other words, it requires the practitioner to have fully completed the life-cycle inventory before system boundaries are chosen. This does not support streamlining efforts to make LCA more time and resource efficient. Furthermore, it requires an impact assessment to establish the "environmental relevance" of a unit process, however, "environmental relevance" is currently a very qualitative process [1]. This does not allow for repeatability due to the judgements required. Although it would be advantageous to be able to select system boundaries based on the environmental relevance of a unit process, it is not practical because of the difficulty in quantifying in a repeatable manner the environmental relevance of a unit process before having assessed the life-cycle system.

One criteria ISO does not mention is selection by "economic value". Economic value is a very practical criteria for system boundary selection because it captures those inputs which have very little mass or inherent energy yet have substantial upstream process inputs (materials and energy) and associated environmental outputs. An example of these inputs is precious metals such as gold or platinum. These materials in the use of a system often are small in quantity (i.e. low relative mass), are not considered energy inputs, but are very costly to the consumer. They also require a significant amount of resources (materials and energy) to extract and process. The economic value of the precious metals provides a proxy for the extent of the upstream energy and material inputs. Furthermore, as processes result in environmental impacts of significant public concern (toxins, greenhouse gases, acid rain, water pollutants, etc.) the economic cost of managing these potential environmental impacts become embedded in the product. As a result, economic value is a valid criterion for system boundary selection. However, the current economic value of products tends not to include the cost of externalities. The LCA practitioner must take caution in using the economic criteria for system boundary selection for evaluations of toxic releases or other low quantity but highly environmentally significant outputs.

The ISO methodology concentrates on mass and energy criteria and states the rules for system boundary selection to be:

"1) Mass is an appropriate decision rule, when using mass as a criterion, would require the inclusion in the study of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled.

2) Energy similarly, a criterion should be established to require the inclusion in the study those inputs that cumulatively contribute more than a defined percentage of the product system energy inputs." [8]

Theoretically, this is a robust method of drawing system boundaries because by considering the total life-cycle mass and energy inputs required to provide a functional unit, one can define a percentage considered significant to include in the study. In other words, if we know the system's grand total of all energy inputs ($E_{System\ Total}$) and all mass inputs ($M_{System\ Total}$), it is possible to systematically move upstream from the functional unit and consider each energy and mass input's (E_i and M_i) contribution to the total. This means calculating $E_{i\%} = (E_i / E_{System\ Total} * 100)$ and $M_{i\%} = (M_i / M_{System\ Total} * 100)$ and comparing these with the defined "cut-off" ratio. If either $E_{i\%}$ or $M_{i\%}$ is greater than the cut-off ratio then one includes the input and its upstream unit process in the system boundary. The practitioner continues to move upstream (or downstream for handling wastes) until all $E_{i\%}$ and $M_{i\%}$ are less than the cut-off ratio. For example, referring to Fig. 3, the energy and mass flows E_1 and M_1 (inputs to unit process 1, products of unit process 2) contribute a percentage of the total system energy and mass inputs ($E_{System\ Total}$, $M_{System\ Total}$) which is greater than the defined cut-off ratio, hence Unit Process 2 is included in the system boundary. Similarly, unit processes 3, 4, and 5 are included in the system boundary because the material or energy flows from them (flows M_2, E_2, M_3, E_3, M_4, E_4) contribute an energy or mass component to the total which is also greater than the cut-off ratio. Unit processes 6 and 7 are excluded from the LCA analysis because the relative energy or mass contribution of the flows 5 and 6 compared to the total system energy and mass inputs is less than the cut-off ratio.

In practice, the suggested ISO method is not practical. The ISO cumulative mass-energy method of system boundary selection is impractical due to the need to calculate the grand totals of a system ($E_{System\ Total}$ and $M_{System\ Total}$). In theory the grand total of energy or mass involves the infinite sum of smaller and smaller contributions to the system. In order to calculate the total one must first make an implicit larger system boundary. How does one choose this initial larger boundary to calculate the totals? It is simply not practical, if at all possible, for the LCA practitioner to attempt to calculate the total mass and energy inputs of any given system. In short, the ISO method of system boundary selection is rigorous and robust in theory, but in practice fails.

Another methodology, presented by BESNAINOU and COULON [13], agrees with the ISO methodology that the mass criteria is not adequate for system boundary selection:

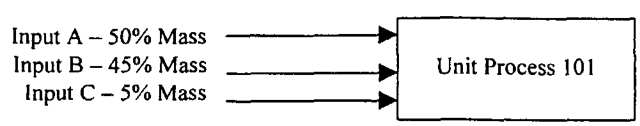

Fig. 2: SBS by mass percentage of unit process inputs

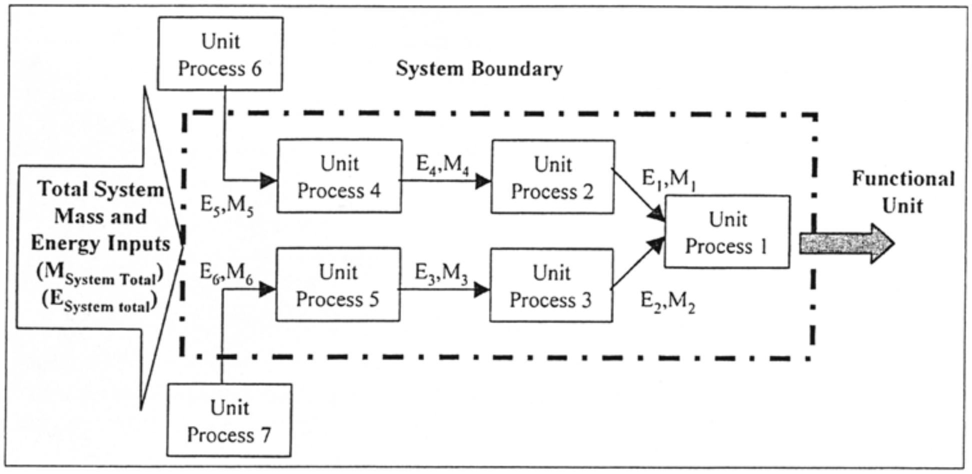

Fig. 3: Cumulative mass-energy method of system boundary selection

"So far, weight has been used as the sole cutoff criterion since this information is always available...This is not satisfactory, however, and a set of cutoff criteria should be used instead of a single criterion."

In response, their methodology defines four criteria for system boundary selection:

1. weight,
2. energy requirement,
3. toxicity (either of the component itself or due to its manufacturing process), and
4. price.

These four criteria are used to qualitatively categorize components to the system to have either a "negligible contribution", "small contribution", or "large contribution" [13]. Although this method has defined important criterion and appears to consider the system as a whole, it remains unrepeatable due to its qualitative nature.

Table 1 lists a number of LCA studies and the method of system boundary selection chosen. None of which the author considers rigorous enough for current LCA work because they are not quantitative. These methods rely heavily on the knowledge and professional experience of the practitioner. As a result, the need exists for a SBS method which is practical, repeatable, rigorous, and robust.

4 The Relative Mass-Energy-Economic (RMEE) Method of System Boundary Selection

The SBS method presented below is a systematic method allowing the LCA practitioner to work upstream from the unit process providing the functional unit. As the LCA practitioner moves upstream a decision is made whether or not each unit process providing a product or service is to be included in the system boundary. This method has been termed the Relative Mass-Energy-Economic (RMEE) method for SBS. RMEE is pronounced "army".

4.1 RMEE step-by-step

4.1.1 Defining Parameters for System Boundary Selection

System boundary selection by means of a relative ratio remains or continues to be the easiest means of determining whether or not a given unit process should be considered

Table 1: System boundary selection (SBS) methods of various lca studies

Authors (Year)	Quote from System Boundary Selection Section of Report	SBS Method	Source
Mann, M.K.; Spath, P.L.; Craig, K.R. (1996)	"Very often, the determination of system boundaries is made based on data availability, and to a large extent, this is how the present analysis was conducted."	Data Availability	[12]
Vigon, B.; Tolle, D.; Evers, P.; Freeman, S.; Landucci, R. (1996)	"general material flow diagrams were constructed focusing on the most important environmental considerations at each stage of the life-cycle"	Qualitative Environmental Relevance	[14]
Hocking, M. B. (1994)	No specific system boundary selection method provided.	Qualitative with consideration of relative energy use.	[9]
Hunt, R.G.; Sellers, J.D.; Franklin, W.E. (1992)	"Second-tier impacts must be investigated, but if in aggregate all of the second-and third-tier operations contribute less than 5 percent to the total, they are excluded from the study."	Set percentage of mass to total.	[11]
Deloite & Touche (1991)	No specific system boundary selection method provided.	Qualitative, non-specified.	[10]
Tyson, K.S.; Riley, C.J.; Humphreys, K.K. (1993)	"We examined a number of previous studies to determine the effect of excluding pre- and post-operational phases." – The study included "Only the operational phase of a fuel cycle"	Energy percentage cut-off based on other studies.	[15]

within the system boundary or not. The question is, "ratio of what?". The ratio applied must act as a proxy for the potential upstream environmental impact of providing a given product or service.

As discussed previously, mass ratio has been used in the past to compare the relative contribution of inputs to a given unit process. Mass as a proxy for potential upstream environmental impact due to the production of a product is valid because products with significant mass require transportation, processing, and extraction of raw materials. These processes require energy and can result in significant combustion related air emissions. However, on its own, relative mass is inadequate because many inputs with significant upstream environmental outputs can have little or no mass, such as natural gas or electricity. These are significant energy inputs.

As a result, relative energy contribution must also be considered in selecting system boundaries. Energy content (measured by heating value) of a product as a proxy for potential upstream combustion related air emissions is valid because the production, distribution, and extraction of raw materials to provide energy can result in significant upstream emissions.

In addition to mass and energy, the RMEE method uses economic value as a third parameter for determining whether or not to include a unit process. Economic value is an important criteria for capturing those inputs with little mass or energy value but do have significant upstream energy inputs and related combustion emissions. Upstream processes that are energy or material intensive often produce costly products or services. The economic criterion identifies these processes. For example, precious metals as an input to a manufacturing process (or a product such as an automobile) would have a low percentage contribution by mass or energy, but could have a significant economic contribution. The production of precious metals is very material and energy intensive and should often be included in the system boundaries.

The RMEE method has been developed with energy and manufacturing systems in mind with a primary interest in air emissions resulting from combustion processes. For this focus, mass, energy, and economic value are valid proxies for potential upstream emissions of products. However, for LCA comparisons concerned primarily with toxic releases, additional parameters (e.g. toxicity of materials) may be required. These additional parameters would be designed to ensure products with a relative low mass, low energy value, and low cost but high upstream releases of toxins, are included in the analysis.

As the cost of monitoring, handling and managing hazardous and toxic substances increases, the economic criteria will better capture these and require inclusion of these unit processes in the system. In certain jurisdictions the cost of hazardous material management will not be reflected in the price of the service or product and could result in exclusion of a number of "small" unit processes which together may result in significant toxic releases. Because current economic systems tend not to capture the external costs associated with toxic releases, the RMEE method is not recommended for LCA studies wishing to quantify toxic outputs. In the future, should external costs be better captured, RMEE may be more appropriate for analyzing LCA systems with toxic emissions. However, in its current form, RMEE is limited to energy and product life-cycle assessments where the decision maker's primary interest is in common combustion related air emissions such as carbon dioxide, hydrocarbons, nitrogen oxides, and sulphur oxides.

Similar to work by BESNAINOU and COULON [13], RMEE uses mass, energy and economic value as criteria for system boundary selection. In the method presented by [13] it is not clear how "negligible, small, and large contribution" is determined. Nor is it clear whether or not one must first identify all the components of the system before one can begin the method for system boundary selection. The Relative Mass-Energy-Economic method presented here attempts to clarify this with a quantitative, repeatable, and systematic method for defining the "contribution" of an input to the whole system.

4.1.2 Defining the Ratio for System Boundary Selection

The "contribution" considered by RMEE is the relative contribution of mass, energy or economic value *to the defined functional unit.* In other words, each input is compared by mass, energy and economic value to the total mass, energy value and economic value of the functional unit. This allows the practitioner to clearly define a ratio to be used to decide whether or not an upstream unit process will be included in the system boundary or not. The lower the ratio, the larger the system boundary, and the more detail included in the study. Because comparative systems share the same functional unit, this also allows appropriate comparison between systems. Comparable boundaries between systems are ensured by declaring the system boundaries to include all those unit processes providing products or services which contribute a given amount to the functional unit by mass, energy or economic value. The result is a quantified system boundary, which can be repeated for different systems in a comparative LCA.

The Steps to Complete RMEE System Boundary Selection

1. Identify and define the functional unit for the LCA.
2. Calculate the total mass, energy, and market economic value of the functional unit, define these as: M_{Total}, E_{Total} and $\$_{Total}$ respectively[1].
3. Define a system boundary "cut-off" ratio (Z_{RMEE}). One might initially define Z_{RMEE} as 0.20, complete the life-cycle inventory and decide whether or not more detail is required to make a comparison. If a more detailed comparison is considered necessary, Z_{RMEE} is lowered and the results considered again (refer to *Table 8*).
4. Begin at the unit process closest to the functional unit, with inputs a, b, c, ..etc.. Quantify the mass (M_i), energy (E_i) and economic value ($\$_i$) of each input (i = a,b,c). Inputs without a meaningful mass or energy value are assigned zero (e.g. electricity is assigned zero for mass, while most process chemicals are assigned zero for energy since their purpose is not an energy input). Document the sources of data, calculations, and assumptions made.

[1] The market value of any product or service is a fluid value due to changes in the economy. However, LCA generally takes a "snap-shot" in time of a system for analysis, as a result a current static value should be used for the market value of products or services for the RMEE method.

5. Calculate $M_{Ratio} = M_i/M_{Total}$, $E_{Ratio} = E_i/E_{Total}$, and $\$_{Ratio} = \$_i/\$_{Total}$. This defines the relative contribution of each input by mass, energy and economic value to the functional unit.
6. If M_{Ratio}, E_{Ratio}, or $\$_{Ratio}$ is greater than Z_{RMEE}, then the upstream unit process of this input is to be included in the system boundary. If neither M_{Ratio}, E_{Ratio}, nor $\$_{Ratio}$ is greater than Z_{RMEE}, then the input is considered "cut-off" and its unit processes upstream from it are not included in the system boundary.
7. Repeat the process for each input of all unit processes included in the system, until all inputs are "cut-off".

The procedure is shown in Fig. 4.

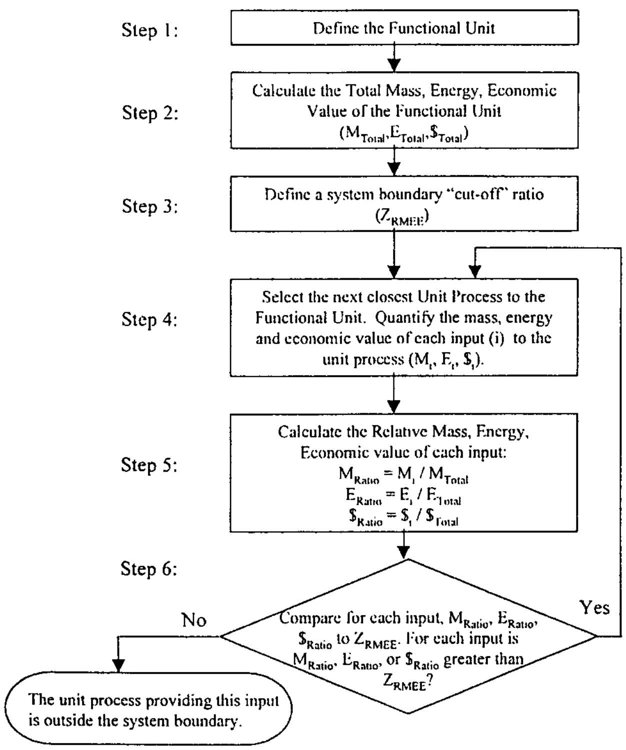

Fig. 4: The RMEE method of life-cycle system boundary selection for LCA purposes

The RMEE method is also used to consider inputs from capital equipment and maintenance by considering the lifetime of capital equipment and frequency of maintenance compared to the needs of the functional unit. The primary advantage of the RMEE method for system boundary selection is, by defining a specified cut-off ratio, independent LCA practitioners can select similar system boundaries for independent analysis.

4.2 The RMEE system boundary selection method demonstrated

The RMEE method is demonstrated for a life-cycle system of the production of ethanol from corn. This example is intended to demonstrate RMEE and should not be considered a complete LCA of ethanol fuel. (For a complete comparison between sources of ethanol fuel, refer to [17]). Fig. 5 (*p. 45*) shows a relatively detailed system for the production of ethanol. The entire system could have been the boundary selected; a relatively arbitrary boundary. There is no indication or measure of how complete the system boundary is at this point, nor if upstream unit processes have been "cut-off" at equivalent points.

Consider the RMEE technique for system boundary selection. Assume we are beginning the LCA and have defined the functional unit to be the products from the corn ethanol plant: ethanol, distillers dried grains and solubles (DDGS) (used as cattle feed), and carbon dioxide for the beverage industry. Following the steps described above:

Step One: Define the Functional Unit
The functional unit is defined as 150 million liters of ethanol, 127,000 tonnes of distillers dried grains and solubles (DDGS), and 97,000 tonnes of carbon dioxide. These are the annual production rates for the given corn ethanol plant [17].

Step Two: Calculate the Total Mass, Energy and Economic Value of the Functional Unit (→ *Table 2*)

Table 2: Calculation of mass, energy and total economic value of the functional unit

Product	Mass (kg)	Energy (MJ)	Economic Value ($)
Ethanol	1.19E+08	3.18E+09	$49.5 Million
DDGS	1.27E+08	1.91E+09	$27.9 Million
CO_2	9.70E+07	0.00E+00	$9.7 Million
Totals:	**M_{Total} = 3.43E+08**	**E_{Total} = 5.08E+09**	**$\$_{Total}$ = $87.1Million**

Note: The values used in this table have been obtained from a study being completed comparing different sources of ethanol fuel by Raynolds et al. [17]

Step Three: Define a System Boundary "Cut-Off" Ratio
For a first iteration, the cut-off ratio (Z_{RMEE}) will be defined as 0.20. (The results of Z_{RMEE} set at 0.10 and 0.05 will also be shown for comparison.)

Step Four: Quantify the Mass, Energy and Economic Value of Each Input to the Current Unit Process (→ *Table 3*)

Table 3: Mass, energy and economic value of inputs to the ethanol conversion unit process for producing the functional unit

Input (i)	Mass (M_i) (kg)	Energy (E_i) (MJ)	Economic Value (1998) ($\$_i$) ($)
Corn	3.80E+08	5.51E+09	$44.8 Million
Natural Gas	8.94E+09	2.64E+09	$7.50 Million
Electricity	n/a	7.20E+06	$90,000
Chemicals (Total)	2.08E+06	n/a	$6.00 Million
Sodium hydroxide	8.40E+05	n/a	no data
Sulphuric Acid	4.00E+05	n/a	no data
Ammonia	8.40E+05	n/a	no data
Water	2.20E+09	n/a	$0.00
Enzymes (Total)	6.30E+05	n/a	$1.00 Million
Enzyme-alpha-amylase	1.30E+05	n/a	no data
Enzyme-gluco-amylase	5.00E+05	n/a	no data
Maintenance	n/a	n/a	$1.00 Million
Construct Plant[a]	no data	no data	$5.10 Million

Note: Values are based on the inputs required to provide the functional unit. These values have been obtained from a study being completed comparing different sources of ethanol fuel [17].
[a]Values for "Construct Plant" are distributed over a 30 year life span.
n/a = not applicable

The current unit process under investigation is the one closest to or producing the functional unit: "Corn Ethanol Conversion". **Table 3** lists and quantifies the mass, energy and economic value of each input to the corn ethanol conversion plant. For the purpose of reporting, document the sources of data, calculations, and assumptions made.

Step Five: Calculate Relative Contribution of Each Input to the Functional Unit Totals (→ *Table 4*)

Table 4: Relative mass, energy, economic value of each input

Input (i)	M_{Ratio} (= M_i / M_{Total})	E_{Ratio} (= E_i / E_{Total})	$\$_{Ratio}$ (= $\$_i$ / $\$_{Total}$)
Corn	**1.10**	**1.08**	**0.51**
Natural Gas	**26.06**	**0.52**	0.086
Electricity	n/a	0.001	0.001
Chemicals (Total)	0.01	n/a	0.06
Sodium hydroxide	0.002	n/a	< 0.06
Sulphuric Acid	0.001	n/a	< 0.06
Ammonia	0.002	n/a	< 0.06
Water	**6.41**	n/a	0.00
Enzymes (Total)	0.002	n/a	0.01
Enzyme-alpha-amylase	0.000	n/a	< 0.01
Enzyme-gluco-amylase	0.002	n/a	< 0.01
Maintenance	n/a	n/a	0.01
Construct Ethanol Plant	no data	no data	0.051

Note: Values in bold are all those greater than 0.20
Note: Values may be greater than 1 due to efficiency in energy or mass transfer to the functional unit. i.e. Most systems will require significantly more energy inputs than the energy value of the final system products or services.

Step Six: Select those Inputs With Relative Mass, Energy, or Economic Value Greater Than Cut-Off Ratio
By comparing the relative mass, energy and economic values from Table 4, with the system boundary cut-off ratio (Z_{RMEE}), defined here as 0.20, 0.10 and 0.05, select all inputs with either M_{Ratio}, E_{Ratio}, or $\$_{Ratio}$ greater than 0.20. This results in the inputs shown in **Table 5** to be followed upstream to their associated unit processes.

Table 5: Inputs to be followed upstream

For Z_{RMEE} = 0.20	For Z_{RMEE} = 0.10	For Z_{RMEE} = 0.05
Corn	Corn	Corn
Natural Gas	Natural Gas	Natural Gas
Water	Water	Water
		Chemicals (Total)
		Construct Ethanol Plant

In this case, for both 0.10 and 0.20 cut-off ratios the same inputs are to be followed upstream. Only at a Z_{RMEE} value of 0.05 is increased detail required.

Step Seven: Move to Next Upstream Unit Process
For the 0.20 cut-off ratio the next tier of unit processes to consider are:
- Transport Corn
- Transport Natural Gas
- Supply Water

For the purpose of demonstration only the corn stream is followed through.

Transport Corn
The inputs to the unit process "Transport Corn" includes the corn itself, diesel fuel, the truck, and maintenance of the truck. Using the RMEE method using Z_{RMEE} equal to 0.20, the only input to be further investigated upstream from "Transport Corn" is corn, as seen in **Table 6** below.

Table 6: Relative mass-energy and economics for transport corn

Input (i)	M_{Ratio} (= M_i / M_{Total})	E_{Ratio} (= E_i / E_{Total})	$\$_{Ratio}$ (= $\$_i$ / $\$_{Total}$)
Corn	**1.11**	**1.08**	**0.51**
Diesel Fuel	0.002	0.01	0.004
Truck Maintenance	n/a	n/a	0
Capital – Truck	0	n/a	0

Produce Corn
Table 7 shows the relative contribution of each input of producing corn compared to the functional unit.

Table 7: Relative mass-energy and economics for corn production

Input (i)	M_{Ratio} (= M_i / M_{Total})	E_{Ratio} (= E_i / E_{Total})	$\$_{Ratio}$ (= $\$_i$ / $\$_{Total}$)
Land drainage	n/a	n/a	0.004
Machinery repairs	n/a	n/a	0.03
Building repairs	n/a	n/a	0.005
Fertilizer - N	0.02	n/a	**0.075**
Fertilizer - K2O	0.0078	n/a	0.02
Fertilizer - P2O5	0.01	n/a	0.02
Crop protectants	no data – low quantity	n/a	**0.05**
Seed	no data – low quantity	n/a	**0.05**
Diesel	0.002	0.003	0.0038
Propane	0.02	0.06	0.0036

As the above table shows, all inputs are "cut-off" for a cut-off ratio of 0.20 and 0.10. When the cut-off ratio is lowered to 0.05, nitrogen fertilizer, crop protectants, and seed are followed upstream to their unit process source.

The final system boundaries with a 0.20, 0.10, and 0.05 cut-off ratio are shown in **Fig. 5** (*p. 45*). It is only fortuitous and case specific that 0.10 and 0.20 boundaries are the same.

For an example of RMEE used in defining the system boundaries for an LCA comparing three sources of ethanol fuel, refer to [17].

4.3 Selecting the RMEE cut-off Ratio (Z_{RMEE})

Up to this point the RMEE method for system boundary selection has provided a systematic and quantitative means to consistently select system boundaries based on a given cut-off ratio. In other words, with a specified cut-off ratio (Z_{RMEE}), different LCA practitioners can complete an analysis on similar systems providing the same functional unit and expect to obtain consistent depth in system boundaries.

However, how does one select an appropriate cut-off? The lower the Z_{RMEE} the more expanded the system boundaries are, and the more detailed data collection must be to com-

Table 8: Selecting a RMEE cut-off ratio (Z_{RMEE}): Author experience based generalizations

RMEE Cut-off Ratio	General Description	Appropriate Use
0.20	• Generally captures only the primary energy, material, and cost inputs to the system. • Typically eliminates need to investigate most unit processes of capital construction (e.g. buildings for a facility, etc.) and ancillary materials.	High-level comparisons of systems, compiling preliminary results, identifying primary unit processes for design improvement.
0.10	• Requires enough detail to include significant ancillary inputs. • Allows practitioner to investigate and understand the implications of more detailed design improvements.	Internal corporate decision making and overall design improvement.
0.05	• Provides a very detailed analysis often including the cost and environmental implications of construction and decommissioning facilities. • Requires substantial resources to complete the life-cycle inventory.	Public claims for superiority of one system over another, assessing systems for environmental output credits, detailed engineering design improvements.

plete the LCA. Appropriate selection of the cut-off ratio depends on the objective of the LCA, the resources available to complete the LCA, and the data sources available. A largely funded academic study with access to detailed industry data may select a cut-off ratio of less than 0.01 to provide a detailed study. However, in general, no specific cut-off ratio can be prescribed for all LCA studies.

From experience of applying RMEE in industry and published work [17], **Table 8** presents three different cut-off ratios and their general appropriateness of use.

A more scientific means of deriving the relationship between the cut-off ratio (Z_{RMEE}) and uncertainty in the results of an LCA is presented in Part 2 of this paper "Part 2: Selecting the Boundary Cut-off Parameter (Z_{RMEE}) and its Relationship to Overall Uncertainty" [19].

5 Conclusions

Based on the authors review, existing methods of selecting system boundaries do not adequately meet the needs of current LCA practice that is quantitative, repeatable, and streamlined. The system boundary selection methodology developed here by the author, called the Relative Mass-Energy-Economic (RMEE) method, is a quantitative means of consistently drawing comparable system boundaries for systems being compared in an LCA. Because RMEE requires only knowledge of material input and output streams (not

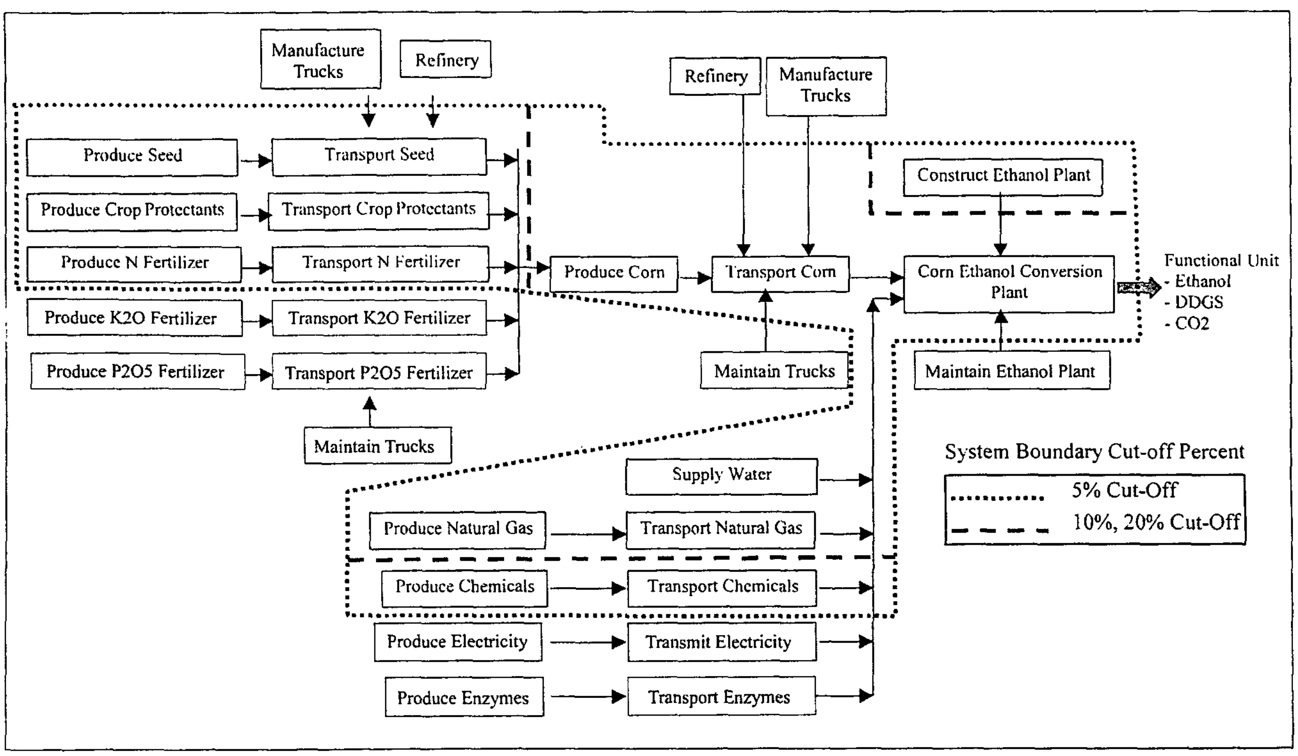

Fig. 5: LCA system for ethanol fuel production

environmental data which is most time intensive) and begins furthest downstream working upstream systematically, it is far more time and resource efficient than other system boundary selection methods. The primary difference of the RMEE method compared to other methods of system boundary selection is that RMEE defines the boundary based on the relative mass, energy and economic value of inputs to unit processes compared to the mass, energy and economic value of the functional unit of the LCA. This leads to a more repeatable method for system boundary selection in LCA and helps ensure comparable boundaries are set for different systems providing the same functional unit.

The RMEE method is particularly well suited for LCA studies comparing energy or product systems based on common combustion related air emissions. The RMEE method is not considered suitable for studies primarily concerned with toxicity because the mass, energy, and economic criteria for inputs do not necessarily capture unit processes with toxic releases to the environment.

In short, RMEE:

- Allows for a fair comparison of different systems providing the same functional unit.
- Quantitatively defines system boundaries making it repeatable.
- Is simple to calculate, requiring only material, energy and service input and output data for those unit processes that will end up in the system boundary. In other words, time and resources are not wasted collecting or estimating environmental data for unit processes not included in the system boundary.
- Produces input and output data that is required for the inventory analysis. Once RMEE is completed, the material, energy and service flows within the system boundary have been quantified, completing a significant portion of the inventory analysis.
- Can be used to determine if capital equipment should be included in the system boundary. The method is not limited to products, services can be considered as well.
- Is designed primarily for evaluation of energy and product systems based on common combustion air emissions.

One current shortfall of the RMEE method is the arbitrary selection of the cut-off ratio (Z_{RMEE}). Further research is being completed to quantify the degree of uncertainty associated with different cut-off ratios. Results of this research are presented in **Part 2** of this paper [19]. The results enable RMEE to move the "art" of system boundary selection to more of a "science".

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